A Laser System Design for the Photo-injector Option for the CERN Linear Collider

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Introduction

This study contributes to the development of the CERN Linear Collider (CLIC). One route to the generation of the required electron injection into this system is through the use of photo-cathodes illuminated with a suitably designed laser system. The requirements of the accelerator and photo-cathodes have led to a specification for the laser system given in Table 1.

UV energy per micropulse	5μJ
Pulse duration	10ps
Time between pulses	2.13ns
Wavelength	≤270nm
Pulse train duration	91.6μs
Repetition Rate	100Hz
Energy stability	≤0.5%
Laser/RF synchronisation	≤1ps
Reliability	10^9 shots

Table 1. Photo-cathode specifications.

Key laser parameters

The key parameters are those for which feasibility needs to be established and they largely determine the system design.

1) *Laser energy stability* - the 0.5% specification in the UV places a very tight requirement on the laser output. Also it must be controllable to this accuracy to meet the varying needs of the photo-cathode due to sensitivity changes etc.

2) *Laser average power* - the laser is required to deliver 430W, a high value for lasers, and one demanding careful design to prevent beam degradation due to thermal effects.

3) *Laser pulse train power* – an average output power in the pulse train of 47kW places severe demands on the laser pumping system.

Basic design features and choices

Pump source

Only diode arrays can meet the shot lifetime requirement of 10^9 shots and have an intrinsically higher stability and lower thermal deposition in the laser material. The cost is higher but development will lead to a reduction in the cost differential.

Wavelength

A wavelength at about 1000nm is chosen since it is most efficiently pumped by laser diodes and can be conveniently converted to the UV using harmonic generation.

Gain medium

There are three principal criteria for selecting the best gain medium for the amplifiers.

The gain bandwidth must support the amplification of pulses of 10ps or less.

The material must be able to achieve a reasonable gain (greater than ~2) with quasi steady state pumping, without excessive losses due to the fluorescence decay. This loss is regarded as excessive if it is larger than the 47kW extracted power in the amplified beam.

The third is the pump power required to generate a reasonable gain in the material.

These criteria point to Nd:YLF as the best option. It also has very low thermal distortion and its birefringence ensures a well polarised output. However care must be taken not to exceed its fracture level of about 20 W/cm.

Amplifier type

Rod amplifiers are preferred, being simpler, better for optical quality and less expensive. Slab amplifiers would need to be considered if required pump powers and thermal deposition rates are too high for rod amplifiers.

Amplification can be carried out using single, multipass or regenerative amplifiers or seeded oscillators. This study mainly concentrates on single and double pass amplifiers and demonstrates that a system based on them is feasible. Four pass amplification can reduce the number of smaller amplifiers at some cost saving but with increased complexity. An injection-seeded oscillator looks a good option for the first stage of amplification especially if the master oscillator provides only low power since it is well suited to giving high power pulse trains with good stability.

System Architecture

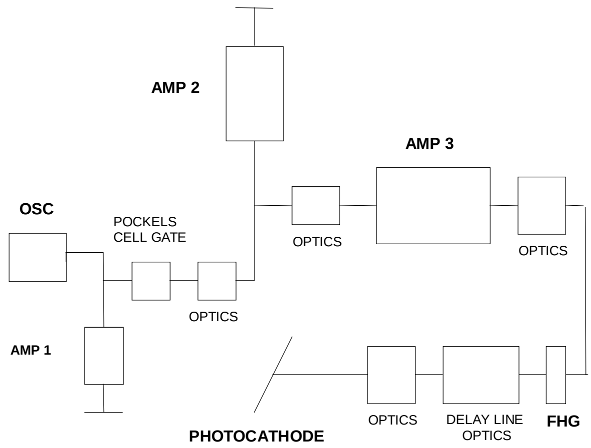


Figure 1. Basic system architecture.

An outline design architecture is shown schematically in Figure 1 and demonstrates the key features of the system.

The pulse train from a cw oscillator with the correct pulse duration and repetition rate and at the correct wavelength is amplified by a sequence of single or double pass amplifiers to the required pulse energy specification. These pulses are converted to the fourth harmonic in a pair of nonlinear crystals and the resulting UV pulse train is relayed to the photo-cathode. Other features of the system are: beam conditioning optics for beam sizing, relaying and filtering; electro-optic devices both for switching out the required pulse train and for fast feed back amplitude control; fast feedback control of pump diode array current.

Detailed design considerations

The system can be conveniently broken down into a number of aspects for detailed analysis:

1) General amplifier design considerations.
2) Amplifier designs.
3) Fourth harmonic generation.
4) Laser damage threshold.
5) System staging - including the disposition of the system components and the design of the beam conditioning optics.
6) Stability - ways to control the intrinsic instabilities of the design through design changes and through the introduction of feedback mechanisms.

Amplification

In this section an analysis is given of the dynamic gain characteristics of both single pass and double pass rod amplifiers subject to a spatially uniform pumping rate and having a spatially uniform input pulse train. Account is taken of: the diode pumping; the amplification of the beam; the depletion of the stored energy by the beam; the fluorescence losses; and the amplified spontaneous emission (ASE).

The approach taken is to specify the output requirements (pulse train power and energy stability) of the amplifier and to look for parameters which minimise the pump energy and maximise the tolerance on the input parameters. The aim is to try to establish 'steady state' operation of the amplifiers since this is most likely to be able to satisfy the stability requirement. An important feature of steady state operation is the time for it to become established, since it is necessary that this is sufficiently short that it does not lead to unacceptably high pumping losses and thermal effects.

Steady state operation

A simple and useful relationship can be found for the amplifier in steady state. In this case the extracted pulse train power is balanced by the difference between the pumping rate and fluorescence losses. This can be written:

$$P_{out}(1-\frac{1}{G}) = \eta_p.P_{abs} - \frac{\pi D^2}{4}.F_{sat}.\frac{\ln G}{2}.\frac{(1+B)}{\tau_{fl}} \qquad (1)$$

where η_p = fraction of the absorbed power (P_{abs}) reaching the upper laser state and we assume a fast energy transfer between the upper state levels.

F_{sat} = saturation fluence = $h\nu/\sigma$
G = amplifier gain
B = additional losses due to ASE
τ_{fl} = intrinsic fluorescence decay time

The factor 2 is for a double pass amplifier (1 for single pass).

For example, inserting the values for Nd:YLF, setting B = 0 and taking the output requirement for CLIC of P = 47kW gives:

$$47(1-\frac{1}{G}) = 0.76P_{abs} - 0.34\ln G.D^2 \qquad (2)$$

and for a 1cm diameter rod with gain x4, absorbed power must be = 46.4 + 0.6 = 47.0kW where the second term (+0.6) is the fluorescence loss.

A comparison between single and double pass amplification can also be made using Equation (1). For amplifiers with the same gain the fluorescence loss term is a factor of 2 less for double pass operation and requires less pump power to reach the same gain. For the two examples above the difference between single and double pass is only an additional 0.3kW for Nd:YLF.

Full calculation

The calculation is characterised by the following parameters:

– The absorbed pump power P_{abs} which is assumed uniformly distributed over the rod.
– The input and output fluences F_{in} and F_{out} of a pulse in the pulse train.
– The diameter D and length L of the amplifier rod.
– The pulse fluence F(z,t) within the amplifier.
– The gain coefficient α(z,t) within the amplifier.

The calculation increments through the pulse train calculating for each pulse its amplification and the resulting gain distribution for the next pulse. An underlying assumption is that the amplifier deals with each pulse sequentially in time, and this may not be the case for multipass amplifiers. However the assumption is valid if, as in the case being considered, the pulse fluence is small compared with the saturation fluence and leads to only a small incremental change in the gain coefficient.

The pulse fluence within the amplifier can be written:

$$F(z,t) = F_{in}\exp\int_0^z \alpha(z,t)dz \quad \text{for single pass} \qquad (3)$$

$$F(z,t) = F_{in}\left[\exp\int_0^z \alpha(z,t)dz + \exp\left(\int_0^L \alpha(z,t)dz + \int_z^L \alpha(z,t)dz\right)\right] \quad \text{for double pass} \qquad (4)$$

The incremental change in the gain coefficient from one pulse to the next has 3 contributions: an increase due to pumping; a loss due to fluorescence enhanced by amplified spontaneous emission, and depletion by the previous pulse. Consequently:

$$\Delta\alpha(z,t) = \frac{\eta_p\eta_R}{F_{sat}}.\frac{4P_{abs}.\tau_S}{\pi D^2 L} - \frac{\alpha(z,t).\tau_S.(1+B)}{\tau_{fl}} - \frac{\alpha(z,t).\eta_R.F(z,t)}{F_{sat}} \qquad (5)$$

where: η_R = level splitting ratio in the upper laser state and it is assumed that the equilibrium in the level populations is re-established in a time very short compared with τ_S.

τ_S = time separation of the pulses in the train

An analysis of ASE is given elsewhere. In order to include its effect in this calculation approximate analytic expressions are used for B as follows:

$$B \approx 0.05.\left(\frac{D}{L}\right)^{0.3}.G^{0.5} \quad \text{for decoupled double pass amplifiers}$$

$$B \approx 0.05.\left(\frac{D}{L}\right)^{0.3}.G \quad \text{for single pass amplifiers} \qquad (6)$$

$$B \approx 0.05.\left(\frac{D}{2L}\right)^{0.3}.G \quad \text{for close-coupled double pass amplifiers}$$

Using these equations the dynamic development of both gain and pulse train fluence was evaluated to find a solution for a specified output pulse train with less than 1% variation over the required pulse train length. Figure 2 shows an example of the output pulse train for the case of a double pass amplifier with its gain switched on in the presence of the input pulse train. The output pulse energy rises to become stable ('steady state') after a characteristic response time. At later times the output is seen to be stable to a very high degree. The process with the minimum response time is critically damped and evaluating a number of different simulations such as in Figure 2 we find the following approximation for critically damped Nd:YLF amplifiers:

$$\frac{4.P_{abs}}{\pi D^2} \approx 240\ kW\ /cm^2 \qquad (7)$$

with a response time $\approx 10.\ln G\mu s$

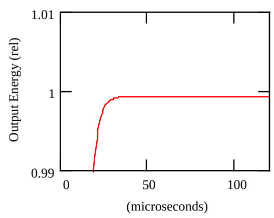


Figure 2. Double pass Nd:YLF amplifier with diodes initiated at zero time and continuous injection of pulse train.

Another important parameter of the amplifier performance is its sensitivity to variations in the pump power and the input pulse energy. These are illustrated in Figure 3 for which the input energy has been decreased by 1% and the pump power is suddenly increased by 1% after 60µs.

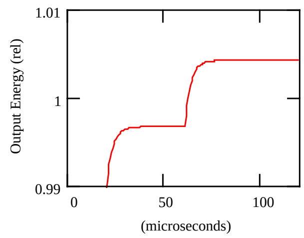


Figure 3. Effect of small changes in input energy and pump power.

The conclusion on sensitivity tests is:

Output variation = input variation / G + pump variation (8)

This is simple to demonstrate analytically by differentiating Equation (1). Consequently by extending this argument through several saturated amplifiers in series, the tolerance to the input pulse energy increases with the total gain of the system. The requirement for stability of the beam energy and pump power of early amplifiers and oscillator is very much relaxed.

We also note a 1/e response time of about 4µs for a sudden pump power change.

We can conclude that good output energy stability can be achieved after an acceptable initial period of pumping to converge to steady state operation. If necessary this initial response time can be eliminated by pumping the amplifier for a short period before switching in the input pulse train.

Double pass amplification gives slightly better performance than single pass but involves additional optical elements.

Diode Pumping of the Rod

We concentrate on the requirements for the final amplifier in CLIC since these are likely to be the most difficult to meet and estimates suggested that an absorbed pump power of 47kW would be required. The problem is reduced to finding the simplest design of pumping chamber which will contain a sufficient number of diode arrays, will couple the diode power efficiently to the rod, and will allow efficient cooling of the rod.

The maximum thermal loading on the rod for the final CLIC amplifier is given by:

$$\text{Thermal Power} = \text{Output Optical Power} \times \frac{1-\eta_p}{\eta_p} \qquad (9)$$

$$= 0.32 \times \text{Output Optical Power} \quad \text{for Nd:YLF}$$

Since the average output power requirement is 430W, the thermal deposition rate is 140W. This can be satisfied using simple flow-tube water immersion and a low flow rate.

The absorption efficiency of the rod has been analysed by Barnes et al[1] and for the case being considered (Nd:YLF at 1% concentration, diode bandwidth = 5nm, average of both polarisations) their results can be reduced to the approximate expression:

$$\eta_{abs} \approx 1-\exp-\left(D/0.42\right)^{0.77} \qquad (10)$$

For example, for an absorption efficiency greater than 80% the rod diameter must be greater than 0.78cm. If the un-absorbed pump is reflected back into the rod for a second pass we can achieve 80% efficiency with rods of diameter 0.39cm.

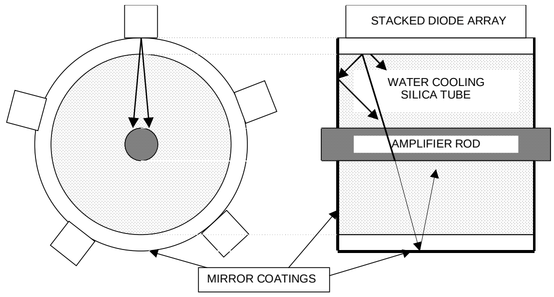


Figure 4. Schematic of diode-pumped amplifier head.

Figure 4 illustrates a simple design suitable to meet the requirements of the CLIC photo-injector system. This design stacks 5 x 9 1cm^2 arrays around a φ1 x 10cm laser rod, providing at a maximum total output well above the required 47kW. The estimated coupling efficiency of this design is 85% and the estimated absorption efficiency is 96%.

Thermal distortion

A significant advantage of YLF is its low value of thermal focusing. From Murray[2] we derive the following relationship for the thermally induced focal lengths in the 'o' ('σ') and 'e' ('π') planes at the principal wavelength of 1047nm:

$$f_o = 2.2.D^2/P_{th} \quad \text{and} \quad f_e = -0.65.D^2/P_{th} \quad \text{respectively} \qquad (11)$$

for D in mm and P in W

or, maximum wavefront error, $\delta_0 = 0.05P_{th}$ or $\delta_e = -0.19P_{th}$ µm

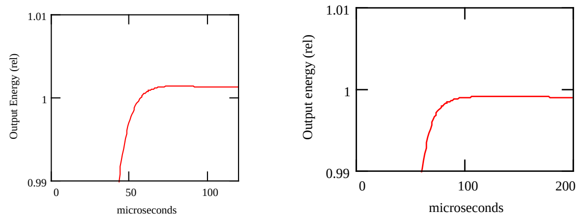
Although Nd:YLF has less thermal distortion than other materials it is still necessary to use spherical and cylindrical optics to correct for the resulting aberration.

Design of amplification system

The specification for the CLIC system is given in Table 1. A mean pulse train power of 47kW is required, and it is important to minimise the required pump power. A key parameter is the total gain of the amplifier system. Suitable oscillators up to 100W output power have been demonstrated so we assume for this design study that 30W is available. 30W input and 47kW output leads to the requirement for a gain of 1600.

A three amplifier system is preferred because it is more conservative and places less demands on pump power and gives less thermal effects in the final amplifier. The total pump power requirement is almost the same for all possible schemes.

The performance of the final amplifier is illustrated in Figure 5 by the dependence of the output train pulse energy on the time after initiation of the pumping, and in the presence of a constant energy input pulse train. The pump power required to achieve the specified performance is 48kW with a rod geometry of φ0.7 x 14cm. The pump pulse duration required to give a 91µs output pulse train with high stability is ≥140µs and at 100Hz the average thermal deposition in the rod is 15W/cm which is less than but quite close to the thermal fracture limit of Nd:YLF[3].



a) b)

Figure 5. CLIC a) final and b) penultimate amplifier giving gains of 4 and 20 respectively.

Operating the final amplifier in double pass would result in a shorter time to reach the steady state and reduce the thermal stress in the rod by about 18%, but with increased complexity.

The penultimate amplifier operating in double pass with a gain of 20 is also illustrated in Figure 5. The required pump power is 16kW for a φ0.5 x 10cm rod. In this case, to ensure that the steady state is reached before the pump for the final amplifier is initiated, the pump pulse duration must be 210µs with a resulting thermal loading on the rod of 11W/cm.

Fourth harmonic generation

Fourth harmonic generation is needed to meet the requirements of the photo-cathode and we have assumed a conversion efficiency of 10%. Although sensible to take a conservative estimate for this design study it is important to improve on this efficiency since this would lead to a significant reduction in the cost of the laser and in the loading of the final amplifier.

Fourth harmonic generation (FHG) uses two second harmonic generation (SHG) crystals in series and, in principle, each SHG process can be 100% efficient for pulses square in space and time. For many systems 50% is generated leading to an FHG efficiency of 25%, but to do this it is necessary to be able to achieve the correct conditions at the crystal. These are:

for high efficiency: $$\left(\frac{\lambda_3 d_{eff}}{\lambda_1 \lambda_2}\right)^2 .IL^2 \succ 0.04 \qquad (12)$$

for sufficient bandwidth:

$$\Delta\lambda.L < \text{value for crystal and wavelengths} \qquad (13)$$

for sufficient angular tolerance:

$$\Delta\alpha.L < \text{value for crystal and wavelengths} \qquad (14)$$

where: d_{eff} = effective nonlinear coefficient in pm/V
I = incident intensity in GW/cm^2
L = crystal length in cm
subscripts 1,2 and 3 refer to the three wavelengths
$\Delta\lambda$ = input pulse bandwidth in nm
$\Delta\alpha$ = input beam divergence in mrad

Equation (13) determines the maximum length of crystal acceptable for the bandwidth of the laser. For 10ps pulses the minimum bandwidth is 1.5cm^{-1} (the transform limit for a 10ps pulse). Having determined the crystal length, or less if appropriate, Equation (12) is used to determine the pulse intensity required to achieve high efficiency. Equation (14) determines the acceptable divergence of the input beam.

Crystal parameters suggest that, using spatially flat top beams it should not be difficult to achieve at least 50% conversion at each stage and an overall conversion efficiency to the fourth harmonic of 25%, a factor of 2.5 higher than assumed for this design study. BBO for both stages looks a good option since it allows the beams to be larger and have the same size. The most critical parameter may be the beam divergence requirement at the fourth harmonic stage as this must be close to the diffraction limit to achieve maximum efficiency. If this proves a problem then KDP offers an attractive alternative.

Optical Damage Requirement

Estimated minimum damage threshold (for anti-reflection coatings) for the CLIC output pulse train (4.2 J in 91 µs) is 40 J/cm^2. Allowing for a safety factor of 4, maximum fluence is 10 J/cm^2 and minimum beam diameter is 7 mm. This criterion allows us to have a calculated beam non-uniformity of 2:1 and still have a factor of 2 in hand.

System Staging

The layout of the system and its optical design are determined by the requirements of beam size and profile at all points in the system. These requirements are:

– The oscillator to generate a single mode beam.

– The beam diameter to match that of the amplifiers.

– For maximum efficiency the beam profile to be close to top hat at the final amplifier, harmonic crystals and photo-cathode.

– To minimise the risk of component damage, the peak to average intensity in the beam at all components should be less than 2.

The single mode generated profile is converted to as close to top hat as possible before the high efficiency amplifier stages. This profile is then image-relayed to subsequent amplifiers, into the harmonic crystals and onto the photo-cathode. The image relays also enable the beam diameter to be matched to the following stage.

The closest it is possible to approach a top hat distribution and meet the requirement that the peak to average intensity must be nowhere greater than 2 is demonstrated in Figure 6 for a 'super-Gaussian' profile. In this case the profile FWHM is 9.4mm or 94% of the final amplifier aperture.

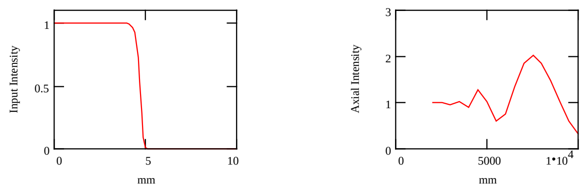


Figure 6. Super-Gaussian and down-stream diffraction pattern.

A schematic of the proposed optical layout of the system is shown in Figure 7.

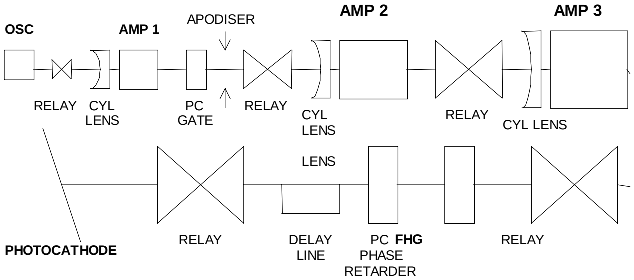


Figure 7. Optical design for the photo-injector laser system.

Conclusions

A design for a laser system has been proposed to meet the specifications appropriate for the CLIC drive beams. The feasibility of this system both in terms of performance and cost have been demonstrated.

References

1. N.P.Barnes *et al*. IEEE JQE 26, 558 (1990)

2. J.E.Murray, IEEE JQE QE-19 488 (1983)

3. W.F.Krupke *et al*. JOSA B3 111 (1986)